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L. L. Tsai

Phase-Delay-Type Artificial Dielectrics

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LEXINGTON, MASSACHUSETTS

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FOR THE COMMANDER

Eugene C. Raabe

Eugene C. Raabe, Lt. Col. USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

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L. L. TSAI
Consultant

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ABSTRACT

This report is based on a survey of the literature on phase-delay artificial dielectrics to examine their suitability for multiple-beam antennas for satellite communications. The conclusions are that arrays of conducting discs appear to be suitable for such application because they can be used with circularly polarized fields and can be built with a desirable index of refraction, in the neighborhood of 1.5. A review of theoretical and measured results is presented, with formulas and curves permitting selection of parameters and permitting determination of the effect of tolerances and of frequency variation. No information was found on the inherent loss of such a medium. In the appendix, digests of 27 selected papers on the subject are presented.

Phase-Delay-Type Artificial Dielectrics

I. INTRODUCTION

The Military Satellite Office of the Defense Communications Agency has asked Lincoln Laboratory to study a multiple-beam antenna capable of producing a variable-coverage radiation pattern. One of the present candidate antennas uses a waveguide-type dielectric lens[1] (or phase-advance artificial dielectric) for beam focusing. The purpose of this study is to examine the available literature on phase-delay-type artificial dielectrics, and if possible, attempt to draw conclusions as to their suitability and potential advantages, if any, in DSCS III applications. Four parameters are also of particular concern: the frequency sensitivity, dimensional tolerances, electrical losses, and capability for circular polarization. A limited search of the readily available literature has been conducted. The findings are as reported in the sequel.

The idea of using obstacle-type artificial dielectric as a phase-delay microwave lens was originated by Kock in 1948.[2] Focusing action of a sphere array lens, a strip array lens, and a disk array lens were demonstrated both theoretically and experimentally. Other investigators have since expanded on this idea, with most of the work occurring in the 1950's. There exist several review articles on delay-type artificial dielectrics,[3-5] with that by Brown[4] being the most comprehensive. Two main schools of thought have been used for the analysis of artificial dielectrics. The first employs classical theory, or what may even be referred to as quasi-static theory.[2,6-16] The second employs transmission line models in which measured suceptances are sometimes needed.[17-25] Depending on one's viewpoint there exist relative advantages for each. One important feature of the second way, however, is that frequency dependence is explicitly shown.

In the sections to come, a brief outline of the two methods is first given. Because of the circular polarization requirement, emphasis is directed to the array of circular disks. Some useful design information for the disk array is next given in Section IV. A few preliminary thoughts on the relative advantages of the phase-delay (disk array) dielectric as compared to the phase-advance-type (waveguide lens) are given in Section V. Following the conclusions and list of references, the Appendix contains a list of summaries for most of the references cited.

II. CLASSICAL METHODS

In the area of classical (or quasi-static) methods, the earliest is the molecular theory of Kock,[2] in which the artificial dielectric is viewed as a loosely structured collection of particles each of which may become polarized under the influence of an externally applied E-field. The ideas may be briefly described as follows. Envisioned is the array of metallic elements (spheres, strips, or disks). Under the influence of the field E_o, charges redistribute on each element, giving rise to some dipole moment m

$$m = \alpha E_o \tag{1}$$

where α is the polarizability (and is known for isolated spheres, rods, and disks from classical static theory). If there are N elements per unit volume, then the polarization, P, is merely the total dipole moment per unit volume, or

$$P = Nm = N\alpha E_o \tag{2}$$

Once P is known, then the relative permittivity, ε_r, is related to the resultant electric field, as

$$D = \varepsilon E = \varepsilon_r \varepsilon_o E = \varepsilon_o E + P \tag{3}$$

$$\varepsilon_r = 1 + N\alpha/\varepsilon_o \tag{4}$$

The two basic assumptions are:

1) Charge distribution on each element can be described as a dipole, and

2) The dipole moment m depends only on the externally applied field E_o as in Eq. (1), i.e., no mutual coupling among elements.

While assumption (1) may be valid for electrically small elements, assumption (2) becomes questionable unless the elements are extremely far apart. Efforts to improve the theory in later work concentrate mainly on corrections to assumption (2).

The first such correction uses the method of Clausius-Mossotti. (A careful treatment can be found in Appendix I and III of Ref. 8.) The idea is that the effects of the neighboring particles on the value of the exciting field may be found through another electrostatic field relationship. A spherical region centered about the dipole of interest is first removed from the array of dipoles. The field within the sphere next can be shown to be

$$E_c = P/3\varepsilon_o. \tag{5}$$

Thus Eq. (2) becomes

$$P = N\alpha(E_o + P/3\varepsilon_o) \tag{6}$$

which when solved yields

$$\varepsilon_r = 1 + \frac{N\alpha}{\varepsilon_o(1-N\alpha/3\varepsilon_o)} \tag{7}$$

Equation (7) represents an improvement over Eq. (4). Although its derivation is quite heuristic, it turns out to be equivalent to the more rigorous dipole field summation method to be described next.

A formal solution for the inclusion of the dipole fields of neighboring elements can be constructed by regarding next the total field as the sum of the applied field E_{app} and the cumulative fields of all other dipoles, E_1. This was done independently in both Ref. 9 and 13. The ideas may be illustrated with a tetragonal array whose lattice spacings are ℓ_1, ℓ_2, and ℓ_1. The correction field E_1, is given by the triple sum over all neighbors as

$$E_1 = \frac{m}{4\pi\varepsilon_o} \sum_{r=-\infty}^{\infty} \sum_{s=-\infty}^{\infty} \sum_{t=-\infty}^{\infty} \frac{2r^2\ell_1{}^2 - s^2\ell_1{}^2 - t^2\ell_2{}^2}{(r^2\ell_1{}^2 + s^2\ell_1{}^2 + t^2\ell_2{}^2)^{5/2}} \tag{8}$$

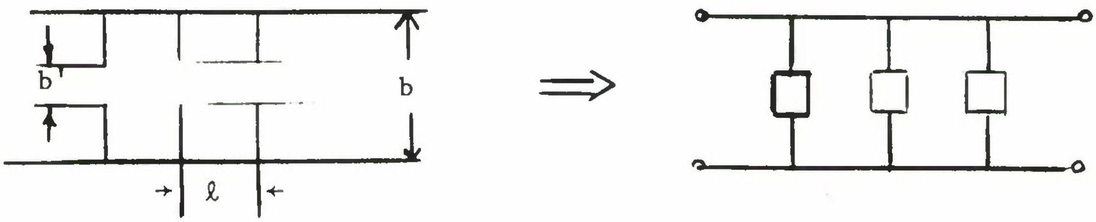
Some difficulties now occur in that the expression above is only conditionally convergent, and thus care is needed in attempts to evaluate it. Kaprielian[13] employed Poisson transforms, while Brown and Jackson[10] employed physical arguments to reduce the triple sum to double sums. An interesting observation made in both Ref. 9 and 13 is that for a cubic lattice, this theory reduces exactly to the ε_r predicted by the Clausius-Mossotti method.

Attempts have also been made to include multipole contributions[9] (since the dipole field alone may not be sufficient for large particles). Unfortunately, the only cases which were tractable were spheres and circular cylinders.

An extension of the static methods to the use of the time-harmonic Green's function has also been examined by Kaprielian.[15]

III. TRANSMISSION LINE APPROACH

In the transmission line method advanced by Cohn,[17-24] an equivalent circuit using transmission line theory is employed to more accurately account for the layer-to-layer interactions. The ideas are as follows. First of all, based on the appropriate boundary conditions, waveguide walls may be inserted perpendicular to the applied E-field.



As illustrated for the strip array above, an equivalent circuit of cascaded susceptances may next be deduced. For the case of an isolated slot, a capacitive iris, the susceptance is known to be

$$B = \frac{4b}{\lambda} \ln \csc \frac{\pi b'}{2b} \qquad (9)$$

Assuming next that this does not change when the slot is in an array environment, network theory may next be applied to determine the refractive index n

$$n = \frac{\lambda}{2\pi\ell} \cos^{-1} \left\{ \cos\frac{2\pi\ell}{\lambda} - \left(\frac{B}{2}\right) \sin \frac{2\pi\ell}{\lambda} \right\} \tag{10}$$

Notice that the frequency dependence is now explicitly shown. In addition, the "bulk" of the layer-to-layer interactions are also properly accounted for. (The only weakness being in assuming that B for a slot in an array is that of an isolated slot.)

While B for the strip array (long slot) is known analytically, it is not available for other arbitrarily configured shapes, e.g., disks. For these structures, an electrolytic tank analog was used to experimentally determine the required susceptance.[18,20,21] The tank analog was first carefully developed so that resistances are the parameter to be measured.[18] Numerous configurations were treated, with among them: circular disks in square or hexagonal distributions, square and rectangular disks, and various apertures.

IV. DESIGN INFORMATION FOR DISK ARRAY

Because the requirements on DSCS make the use of circular polarization desirable, the strip array artificial dielectric may be excluded from further consideration. Among the array configurations which can allow CP operation, metal spheres, dielectric spheres, and disks are potential candidates. It turns out, however, that for spheres the magnetic fields are also disturbed, resulting in a relative permeability μ_r less than unity.[2,8,9] This has the effect that the index of refraction achievable is also lower. Thus, for optimal operation, the disk array would be the prime candidate, since it not only achieves higher refraction index, but also weighs less. In this section, pertinent design information on disk array artificial dielectrics is given. Attention is addressed not only to the refraction index as related to disk sizes and cell spacings, but also to dimensional sensitivity and dispersion characteristics.

Consider first the measured values of the relative permittivity of an array of circular disks from Ref. 9, shown in Fig. 1. (For disk arrays, the relative permeability $\mu_r \approx 1$ because the magnetic field is practically undisturbed, thus $n = \sqrt{\varepsilon_r}$.) The results have been obtained by measuring capacitance on a Schering bridge at 1000 Hz. Copper disks 1/2" in diameter and 1.5×10^{-3} inch thick embedded in ebonite foam comprise the model. Notice that a rather wide range of parameter values had been considered, and the usual ranges of practical n for lens applications are thus adequately covered. Consider next the theory supplied by Ref. 10, with the comparison of measured (Ref. 9) and calculated ε_r shown in Fig. 2. For the theory, the dipole field interactions are expressed as a triple sum, but the following approximations were used: For $b/a > 0.6$, the inter-layer coupling is assumed negligible, and summation occurs over only one sheet, with the result

$$\varepsilon_r = 1 + \frac{a}{b[1.5(a/d)^3 - 0.36]}, \tag{11}$$

where the dimensions are as defined in Fig. 1. When $b/a < 0.6$, on the other hand, the approximation is used where each stack of disks in the array is treated simply as a cylinder, with

$$\varepsilon_r = 1 + \frac{\alpha' N/\varepsilon_o}{1 - \alpha' N/2\varepsilon_o} \tag{12}$$

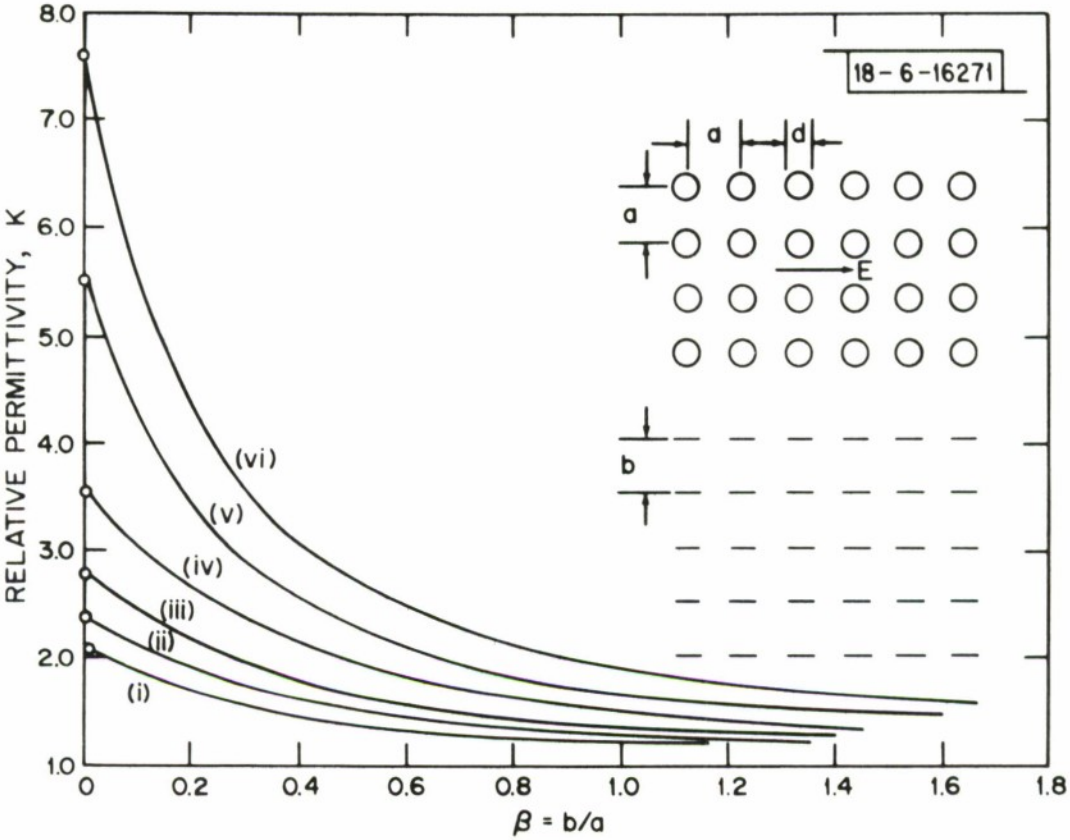


Fig. 1. The measured relative permittivity of a rectangular array of circular disks.

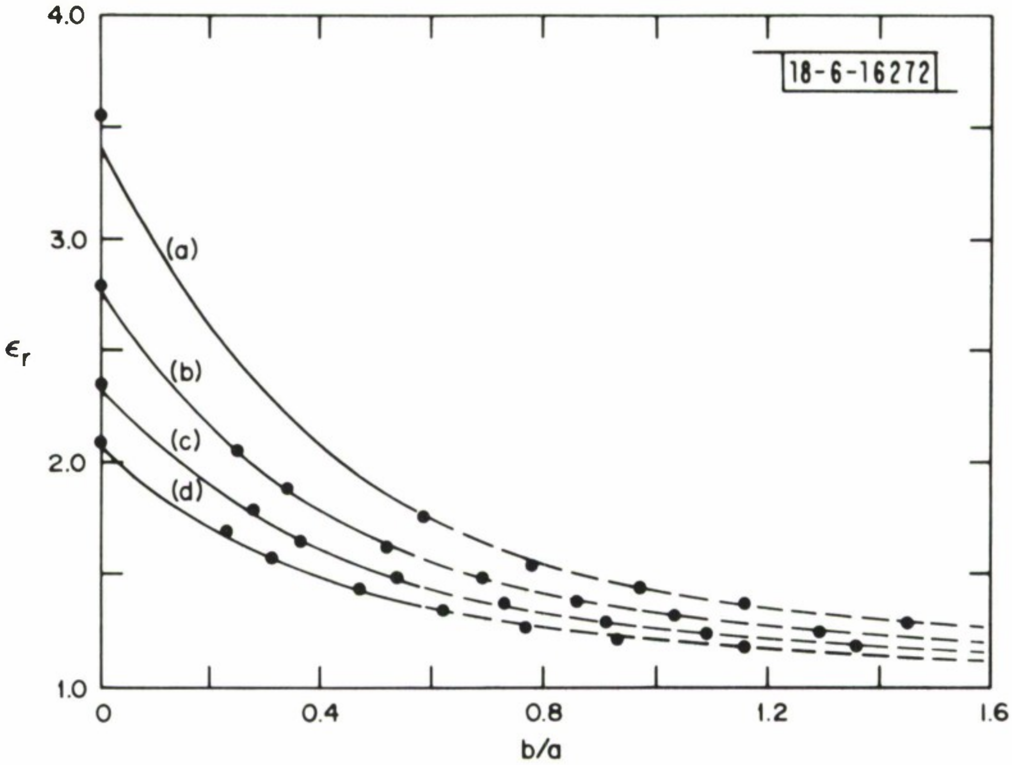


Fig. 2. Comparison of calculated and measured ε_r for a circular disk array.

where

$$N = 1/a^2, \ \alpha' = \frac{\pi \varepsilon_o d^2}{2} \left[\left(1 - \frac{0.441b}{d}\right)^2 + \frac{0.058b^3}{d^3} \left(1 + \frac{0.441b}{d}\right) \right] \tag{13}$$

Because good agreement between theory and measurement is exhibited, the simple formulas of Brown and Jackson,[10] in Eqs. (11) and (12) may be regarded as accurate, and useful for engineering applications.

To lend further suhstantiation to the above conclusion, it is worthwhile to note that the measured results of Cohn[24] via the electrolytic tank method, Fig. 3, also agree closely with the measured results of Kharadly and Jackson.[9]

Equations (11) and (12) have been used to calculate a detailed parametric study of ε_r for the disk array. The results are as shown in Fig. 4. These curves should be useful to the lens designer in relating the desired index of refraction, $n = \sqrt{\varepsilon_r}$, to the necessary disk sizes and spacings. Aside from this direct application, Fig. 4 should also be useful in assessing the effects on the index due to dimensional tolerances. As an example, consider the ε_r centered around 2.5 for a b/a (layer spacing/disk separation) fixed at 0.25. It may be noted that for d/a ranging from 0.84 to 0.86, ε_r varies from 2.44 to 2.58. Thus, a 1.7% change in d/a (dish diameter/disk separation) causes the ε_r to shift 5.6%. The variations of manufacturing inaccuracies in disk diameters may thus be correlated to errors in the index: depending on the frequency of operations, and thus the disk's physical size d, these may be translated directly to tolerance specifications in microns or mils.

It is also interesting to examine the possibility of using other than a

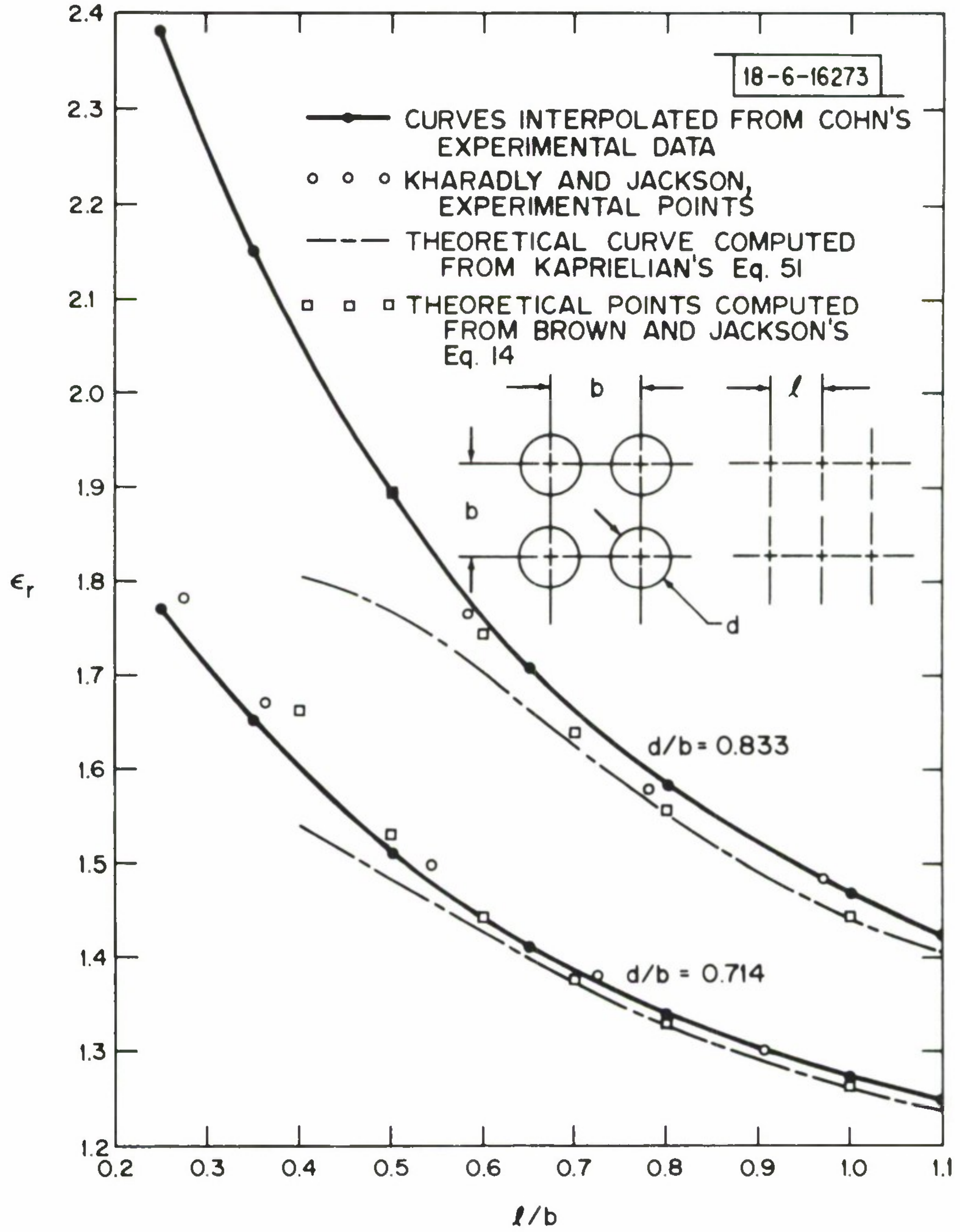


Fig. 3. Comparison between measured values by Cohn [4], Kharadly and Jackson [9], and the calculated results of Brown and Jackson [10].

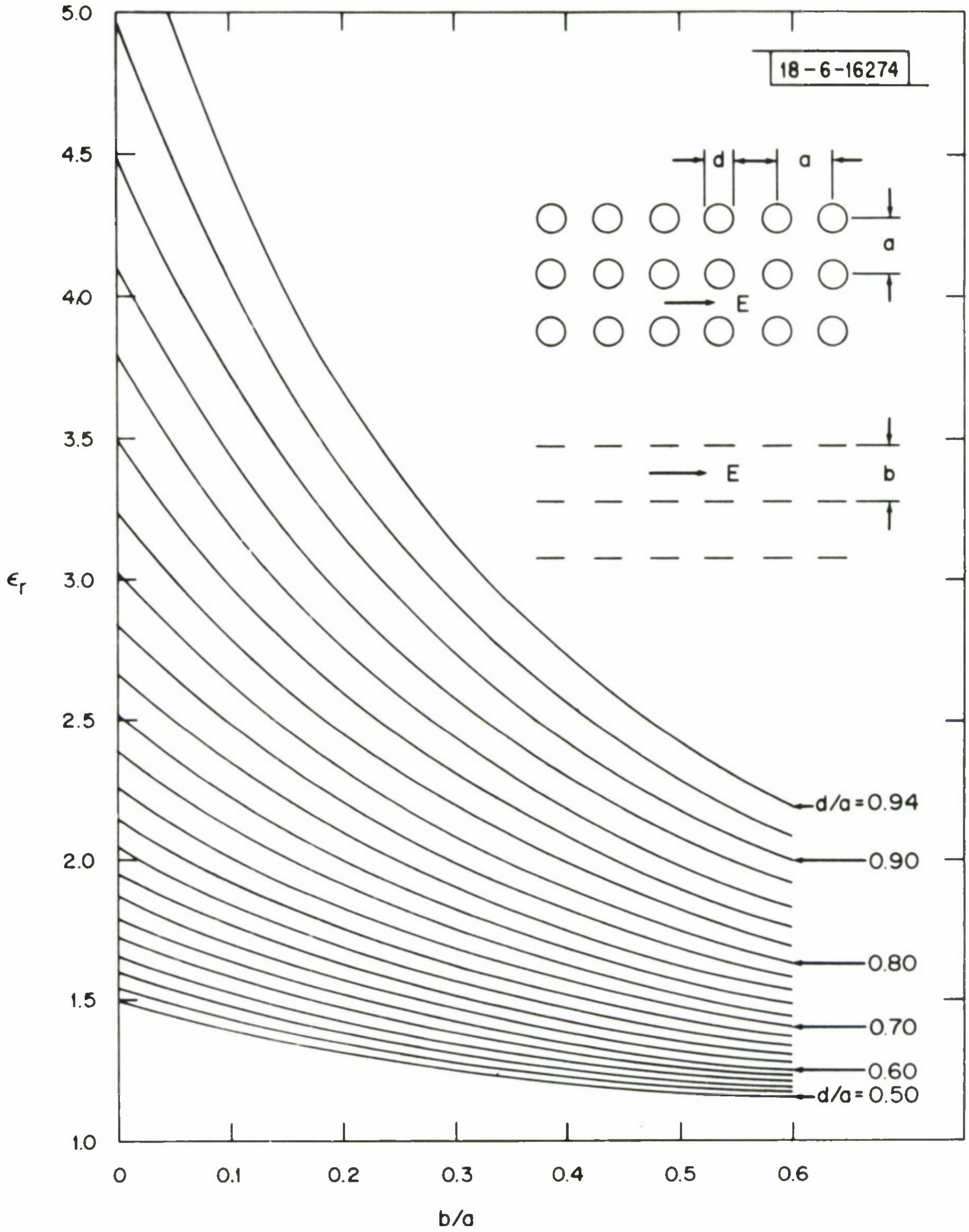


Fig. 4. The relative permittivity of a tetragonal array of circular disks (computed using Eqs. (11) and (12)).

square distribution of circular disks as the lens medium. Toward that end the electrolytic tank measurement results of Cohn[18] are shown in Figs. 5-7 for the cases of a square distribution of circles, a hexagonal distribution of circles, and a square distribution of square disks. It may be noted in passing that the hexagonal distribution apparently yields somewhat higher index of refractions than does the square distribution.

As has been stated earlier, another factor of interest is the bandwidth of the lens medium. To gain some insights into the basic dispersion characteristics of the phase-delay artificial dielectric, it will be useful to examine some experimental results. Cohn[23] gave the waveguide simulator measured refraction index as a function of frequency, for the strip array. These are as shown in Figs. 8-10. It can be readily seen that the index may be held to be virtually constant, particularly if one is willing to allow the strip widths to be quite small electrically. For the case of the array of circular disks, the measured dispersion characteristics by El-Kharadly[11] are useful (shown in Fig. 11). Again, n can be made quite constant. Thus the phase-delay medium can be concluded, based on experimental evidence, as an inherently broadband device. (Transmission-line-model theory also supports this.[4]) In examining the dispersion characteristics, one question naturally arises. How small must the disk sizes be in wavelengths in order for the design information given in Figs. 1-7, calculated from quasi-static method, to still remain valid? The conclusion that had been unanimously reached,[4,9,11,12] though it had not been directly correlated with the dispersion curve in Fig. 11, is that the disk diameters as well as cell spacings must be smaller

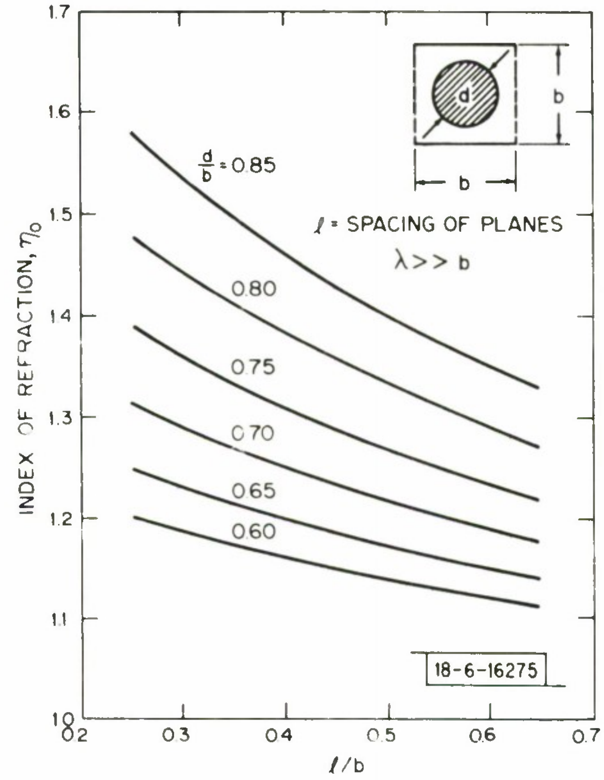


Fig. 5. Electrolytic tank measured values for a square distribution of circular disks.

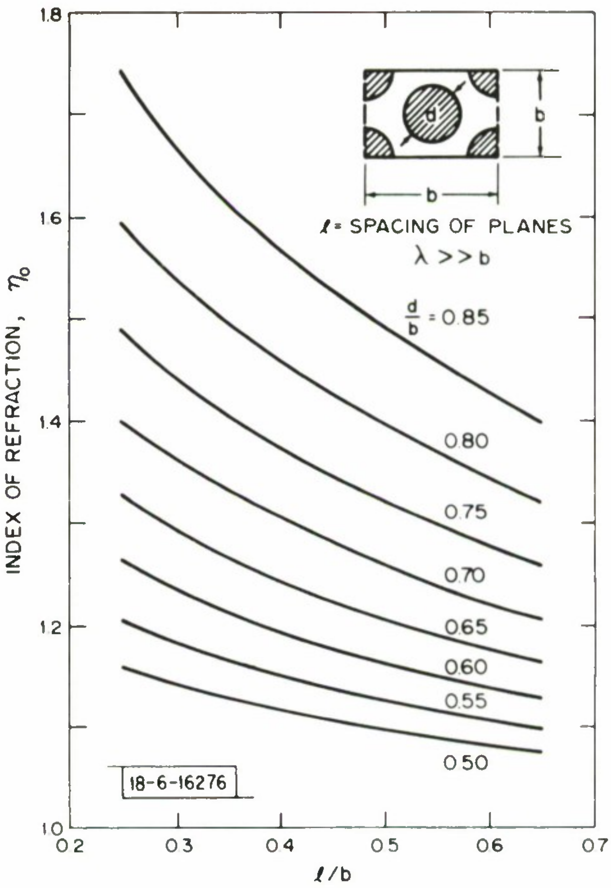


Fig. 6. Electrolytic tank measured values for a hexagonal distribution of circular disks.

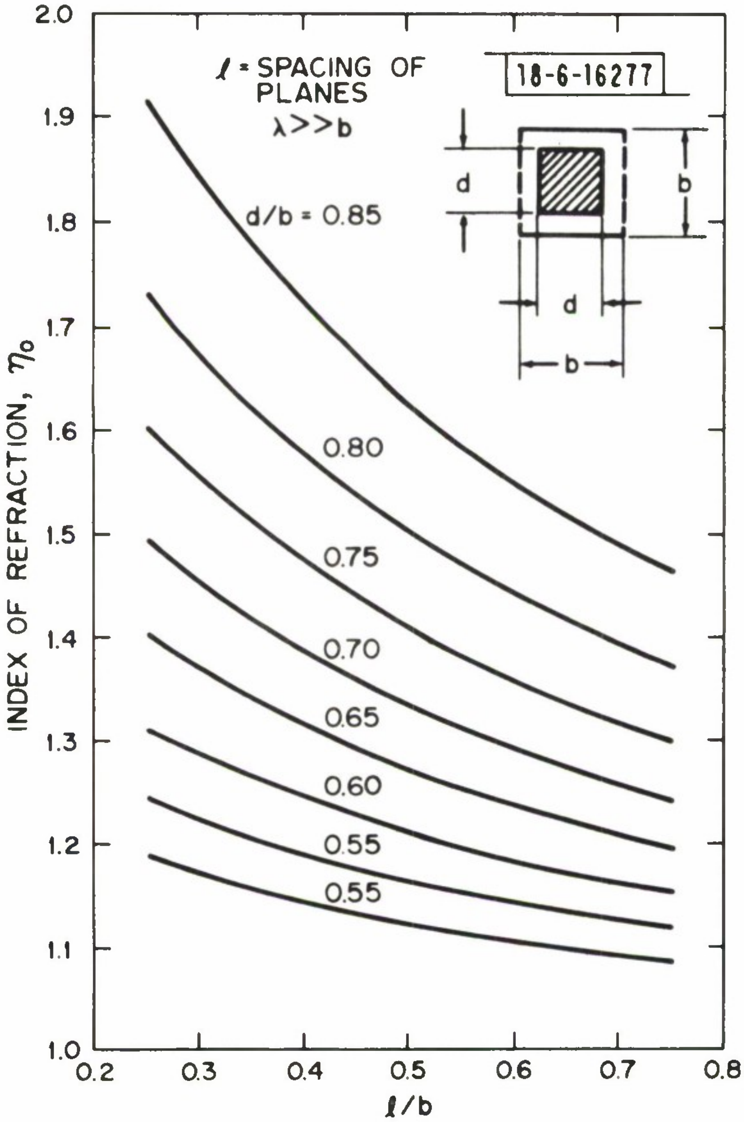


Fig. 7. Electrolytic tank results for square distribution of square disks.

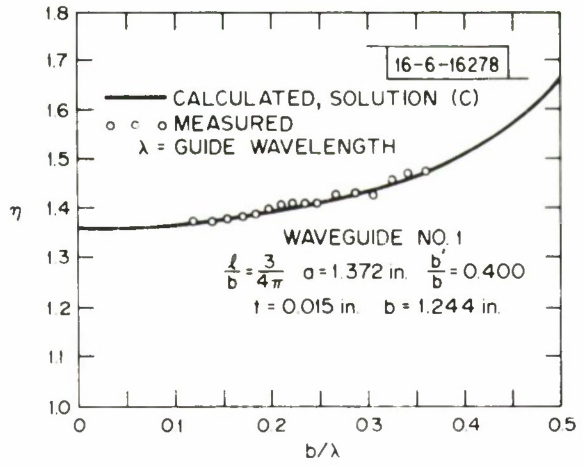


Fig. 8. Measured index of a strip array.

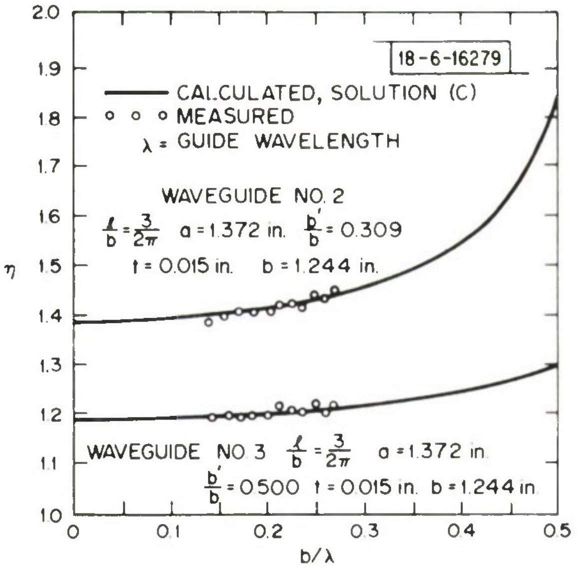


Fig. 9. Measured index of two strip arrays.

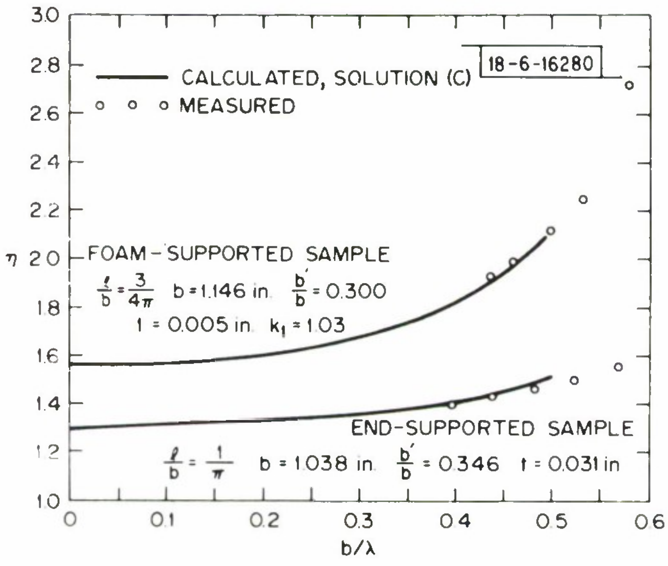


Fig. 10. Measured index of a strip array in free space by a dielectrometer.

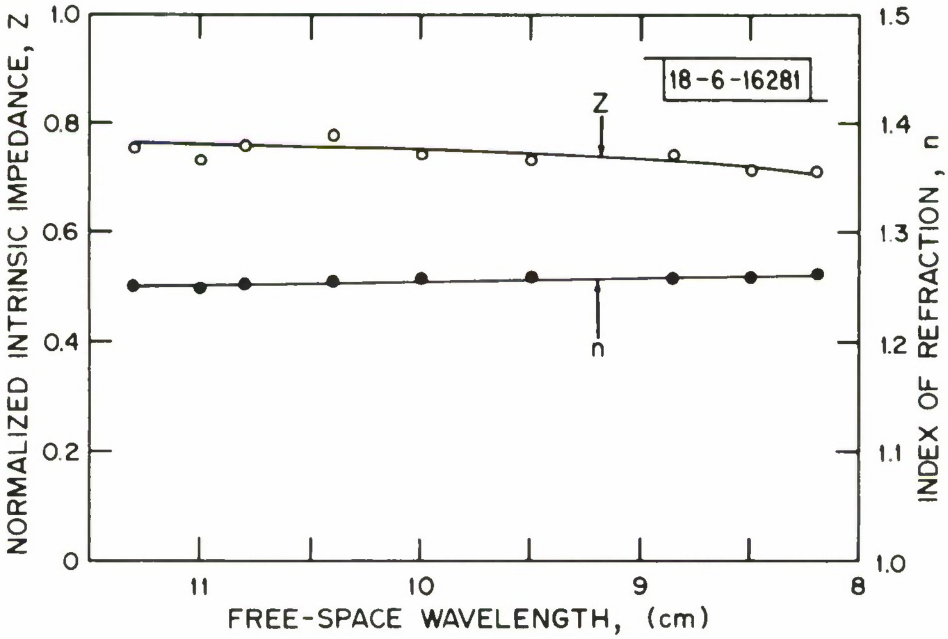


Fig. 11. Measured refraction index of an array of circular disks.

than one-tenth the operating wavelength. Except for difficulties in holding mechanical tolerances, this would be a desirable goal, since it also makes the structure broadband.

Two other quantities which have received some attention are the effects of disk thickness[19] and possible adverse effects of reactive fields at the interface between air and the artificial dielectric.[4,12,14] Even though they represent worthwhile academic problems, their effects on practical lens performance should be quite insignificant.

The question of losses in the artificial dielectric (ohmic losses internal to the medium rather than reflection power loss at the interface) is an area which has received very little attention. In fact, it is recommended in Ref. 4 as a potentially fertile area for future research.

V. PHASE-DELAY VERSUS PHASE-ADVANCE ARTIFICIAL DIELECTRICS

Phase-delay-type artificial dielectric possesses one very important advantage over phase-advance-type artificial dielectrics. This is illustrated in Fig. 12 by their respective dispersion characteristics. Because the phase-delay-type array simulates with its "particles" a real dielectric, it can operate over a much broader <u>bandwidth</u>, than does the phase-advance-type which has the dispersion properties of waveguides. For practical applications, this important requirement may preclude other design considerations, which are treated next.

Consider the representative fabricated lens models for the two dielectrics. For the advance-type, "egg crate" stacks of square waveguide (as in Ref. 1) using thin and lightweight sheets of titanium may be constructed. For the

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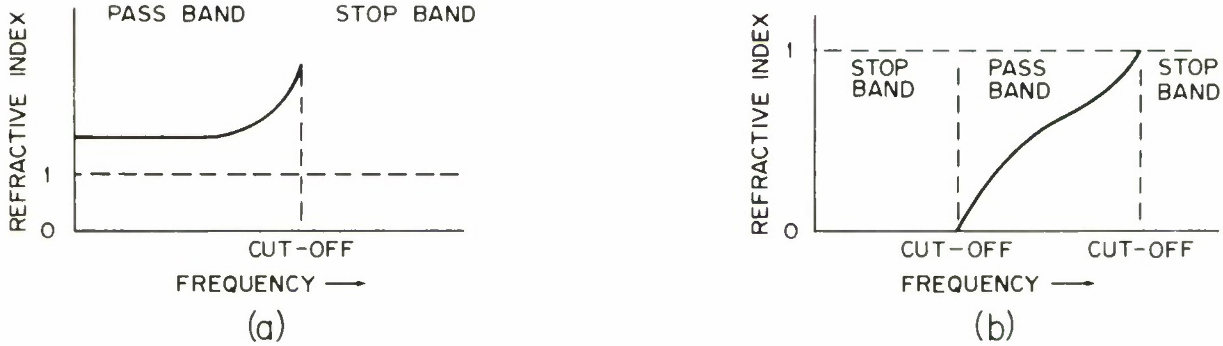


Fig. 12. The dispersive properties of artificial dielectrics (a) Delay dielectrics; (b) Phase-advance dielectrics.

delay-type, stretched dielectric sheets with metal-spray-painted disks can be formed in a stack (a method originally suggested by Kock[2]). Comparing the two structures, the weight should be comparable, with perhaps the delay-type being somewhat lighter. In terms of mechanical rigidity, the advance-type should hold a rather distinct edge. The volume of the two lens would again be almost the same. In terms of ruggedness and ability to withstand environmental factors such as ultraviolet radiation, the advance-type again holds a definite advantage. Electrical losses should also be smaller in the advance-type.

Along the lines of manufacturing ease, depending on one's viewpoint, either may prove preferable. Mechanical tolerances, however, may tend to be more critical for the delay-type. Specifically the disk sizes are already electrically small but the dimensions still need to be accurate, and in addition the stacks of sheets must be properly aligned disk-wise in order for available design data to apply. Both structures offer manufacturing flexibility to designer specified variations in the refraction index, in that changes in dimensions can easily accomplish this goal. As for over-all cost, the advance-type should prove more advantageous, since it has an expectedly longer service life-time.

VI CONCLUDING REMARKS

In concluding this literature search, it can be remarked that the methods thus far developed appear to be quite adequate for the prediction of the refraction index of phase-delay-type artificial dielectrics. A large amount of useful information exists in the references, with only a minor portion being reported here. The summaries in the Appendix may also be of aid if more details are desired.

APPENDIX I

Summaries for most of the references cited are included in this appendix. The numbers correspond to those in the reference list.

2. W. E. Kock, Bell Tech. Journ., 27, 58-82 (1948). This paper represents the genesis of the ideas of using a metallic delay medium for microwave lenses. The conception of the idea lies in fundamentals of classical field theory where a solid dielectric may be viewed as a collection of particles which becomes polarized under the influence of an externally applied electric field $\vec{E}$. This contributes a net polarization $\vec{P}$ which gives rise to $\vec{D} = \varepsilon\vec{E} = \varepsilon_o\vec{E} + \vec{P}$, or an effective permittivity ε different than ε_o. Experimental and molecular theory results for an array of conducting spheres are first given. It was found also that thin rather than thick obstacles should be used since the latter deforms the magnetic field as well, leading to a less than unity permeability μ or diamagnetic effects, and thus a net lowering of the realizable index of refraction $n = \sqrt{\mu_r \varepsilon_r}$. The theory and fabrication ideas for a strip array lens suitable for linear polarization is next given. (The E vector should be perpendicular to the strip length but also lie in the plane of the strip.) Measured patterns from 3.8 to 4.4 GHz of a strip lens with a point feed in Fig. 9 dramatically demonstrated the focusing capabilities of an artificial dielectric lens. Configurations of metal spray-painted grids are next given together with a proposal for juxtaposing strips for achieving high refraction index (though at larger reflection losses).

Additional lens considerations are also given. It was concluded that lens elements should not be allowed to approach resonant lengths, in order to keep dispersion low. One possible means of minimizing reflection effects was to allow an off-set of one half of the lens from the other. A potential advantage noted for the strip lens over conventional waveguide lens lies in the non-necessity to use steps, which tend to introduce diffraction effects.

3. C. Susskind, British Inst. of Radio Engineers Journ., XII. No. 1, 49-62 (1952). Presents review of state-of-the-art in delay-type artificial dielectrics up to 1952. The molecular theory approach and the Clausius-Mossotti method (which accounts for dipole mutual interactions) are presented. A useful list of the electric and magnetic polarizabilities (static) for variously shaped conducting objects are tabulated. These include isolated spheres, cylinders, circular disks, elliptical disks, strips, and square disks, with varied polarizations. For the circular disk $\alpha_e = 16a^3/3$ and $\alpha_m = -8a^3/3$ where a is the radius. Results for refractive index based on the above static parameters are also given.

The transmission line approach for strip medium is also reviewed. Extensions by Cohn to disk medium are also presented, together with comparisons to the Clausius-Mossotti theory.

A scattering theory approach by Lewin (a generalization of the Mie theory) for array of spheres is also quoted, together with what it reduces to for the refractive index in large wavelength limits. The theory is tried for the disk array, but no concrete results or formulas are given.

Mention is also made of the interface reflection problem and the dispersion characteristics.

4. J. Brown, "Artificial Dielectrics," Progress in Dielectrics, Vol. II, (Wiley, 1960) 194-225. A comprehensive review of obstacle-type phase-delay artificial dielectrics is given. A historical development is first given followed by a classification of the types of artificial dielectrics. Classical theory used for phase-delay-type medium is carefully outlined. The use of transmission line modeling then allowed for some inclusion of frequency dependence. Attention is also addressed to the problems of interface reflection and oblique incidence problems. Eighty-one references are cited.

The chapter is well written and for anyone looking into phase-delay-type artificial dielectrics, this should be the first article to be read.

5. J. Brown, "Lens Antennas," Chap. 18, Antenna Theory, Part II, edited by Collin and Zucker, (McGraw-Hill, 1969) 104-150. Lens antennas in general are reviewed. Coverage includes phase-delay-type artificial dielectrics, phase-advance-type dielectrics (waveguide lens), homogeneous lens, scanning and broad beam cases, and non-homogeneous lens (Luneburg lens).

6. G. Estrin, J. Appl. Phys., Vol. 21, 667-670 (1950). The permeability μ for an array of thin circular disks with the H-field perpendicular to the disk face is obtained theoretically. (Notice that this would not be the polarization used in an artificial dielectric lens). Time harmonic analysis is performed by separation of variables in oblate spheroidal coordinates for an isolated disk. The currents thus found can be integrated in closed form for radius a small, yielding the magnetic dipole as $m = -8/3a^3\ H_{applied}$. (This result was known to Rayleigh also in 1897.) For the case of a sparse lattice

of disks, the molecular theory of Kock can next be used to predict a relative permeability μ_r smaller than unity. It was also pointed out that because anisotropic behaviors are present, a dyadic description is needed.

7. G. Estrin, Proc. IRE, 821-826 (1951). The effects of anisotropy in a three-dimensional array of conducting circular disks are theoretically treated. Formerly derived dyadic field equations are first transformed into a new coordinate system which unitizes the permeability dyad or matrix. Arguments from complex crystal optics theory are next applied. Though little results are presented, the main conclusions seem to be that in lens applications, because the angle of incidence is not always perpendicular, anisotropic effects may become severe.

8. R. W. Corkum, Proc. IRE, 574-587 (1952). Theory and measurement for artificial dielectric comprising array of metal or dielectric spheres is presented. A detailed justification from fundamentals for the derivation of the Clausius-Mossotti expressions for dielectric constant of a collection of particles is given in the appendices (Appendix I for ε and Appendix II for μ). The electric and magnetic susceptibilities ($K_e = \varepsilon_r$ and $K_m = \mu_r$) are next found using this theory for both the case of a lattice of metallic spheres and then dielectric spheres. The theory is perhaps over-extended to the situation where the metallic spheres are so closely packed so as to be touching. Here the maximum achievable refraction index is found to be 1.273.

Measurements for n, K_e and K_m using waveguide sample inserts are performed at 5 GHz. Results are presented in Table I (for metallic spheres) as function of the number of rows of spheres. The refractive index settles to a steady state value rather quickly and agrees well with theory. Table II gives the results for dielectric spheres. Here the diamagnetic effects are not as strong as metal spheres and higher index n is achievable. A speculation on the interface reflection problem is also offered.

9. M. M. Z. Kharadly and W. Jackson, Proc. IEE, 119-212 (1953). A comprehensive treatment of obstacle-type artificial dielectrics is given. Both theory and measurements are supplied. The structures considered consisted of both two-dimensional and three-dimensional arrays. Among these square and rectangular distributions of cylinders, strips, spheres, disks, rods, and imperfectly conducting spheres are treated.

The theory is quasi-static in that the molecular theory of Kock is extended by inclusions of dipole and multipole interactions. The inclusion of dipole contributions makes the theory equivalent to that of Clausius-Mossotti (exact equality for cubic lattice). The multipole contributions are not as easily tractable and turn out tobe practical only for conducting spheres with cubic lattice, and circular cylinders. Experimental results for the relative permittivity are obtained by measuring on a Schering bridge at 1000 Hz the capacitance of a specimen comprising a portion of the infinite array of metal obstacles.

Among the two-dimensional arrays, circular cylinder is the first treated. Compared to measurements in Fig. 4 the molecular and dipole theory gave adequate accuracy for $d/a < 0.5$ (diameter of cylinder/cell width). The multipole theory gave almost exact agreement up to $d/a = 0.75$. For an array of thin strips, the multipole approach was not extendable. Howe and Whitehead (in apparently unpublished work) had obtained an "exact" electrostatic solution, however. Comparison of the molecular theory, the Clausius-Mossotti theory, and this exact theory with measurements in Fig. 6, yielded the same conclusions as the cylinder case.

For three-dimensional arrays, the first case considered is conducting spheres. The dipole theory is written as a triple sum (similar to that of Kaprielian, 1955). Multipole fields for cubic array of spheres uses the work of Rayleigh, (1892). Comparison of these to measurements again finds that for $d/a < 0.5$, the molecular and dipole theory is adequate. Multipole theory on the other hand, gave accurate permittivity all the way up to $d/a = 1$. (Fig. 8). Next considerations are extended to a tetragonal array of circular disks. Account for dipole contributions in this case closely parallels, but is not as general, as the later work of Kaprielian (1955). A comparison of the molecular theory and dipole theory to measurements is given in Fig. 11. Adequate accuracy for both theories exists for d/a (disk diameter/cell width) as high as 0.7. In Fig. 12 a parametric study (measurement) as d/a varies, and as a function of b/a (layer spacing/cell width) is presented, and these should be useful in DSCS lens design. Data here were obtained using 1/2" diameter copper disks embedded in ebonite foam. (In a later paper, Brown and Jackson, 1955, corresponding theory will also be supplied.) The parameters b/a ranged from 0.2 to 1.7 and d/a varied from 0.669 to 0.952, thus fairly high optical occupancy ratios were used.

The case of an array of rods in a cubic lattice and imperfectly conducting spheres is also treated. Three useful main conclusions have also been drawn:

(1) Dipole interactions alone do not account for all effects accurately when the fill rate of metal is greater than 50% of volume.

(2) Flat structures are not diamagnetic when the applied magnetic field is parallel to the plates, thus the achievable refractive index is higher.

(3) The quasi-static results thus determined are believed to be applicable provided the operating wavelength is greater by at least a factor of 10 than either element size or lattice spacing.

10. J. Brown and W. Jackson, Proc. IEE, 37-42 (1955). Tetragonal array of circular disks is treated. This work represents an extension of the theory of Kharadly and Jackson in that formerly conditionally convergent series are now artfully summed based on physical arguments, giving now more reliable results when inter-layer spacing becomes small.

A clear and easily understandable derivation of the molecular theory is first given (Eq. (5)). When dipole interactions are included, it then becomes necessary to deal with the triple sum in Eq. (9). A method according to Lorentz can be used to show that this is equivalent to the result by the Clausius-Mossotti relation. In doing so, however, the dependence of the permittivity on b/a (layer spacing/cell width) is approximated out, thus design information is lost. To contend with this, the conditionally convergent triple sum (i.e., if summed wrt one index first, then convergent, but not so if other index is used first) is re-examined.

The following rationale is used:

a) For $b/a > 0.6$, then the inter-layer coupling should be less important than intra-layer coupling. Thus they are ignored and one sums over one sheet only. This reduces the problem to a double sum and one obtains Eq. (14)

$$\varepsilon_r = 1 + \frac{a}{b[1.5(a/d)^3 - 0.36]}$$

where d = disk diameter, a = cell width, b = layer spacing.

b) For $b/a < 0.6$, then the reverse role of importance is present. Thus one simply views each stack of disks as a virtual circular cylinder, and use its polarizability, with the result

$$\varepsilon_r = 1 + \frac{\alpha' N/\varepsilon_o}{1 - \alpha' N/2\varepsilon_o}$$

where

$$N = 1/a^2, \quad \alpha' = \frac{\pi\varepsilon_o d^2}{2} \left[\left(1 - \frac{0.441b}{d}\right)^2 + \frac{0.058b^3}{d^3}\left(1 + \frac{0.441b}{d}\right)\right]$$

A comparison of the theory and the measurements of Kharadly and Jackson (1953) is shown in Fig. 2. (It should be pointed out that only four cases are shown here whereas six were measured.) The agreement is excellent. The breakover point where either theory (a) or (b) presides is empirically deduced to be $b/a = 0.6$. By either differentiating the above simple expressions or by calculating a more detailed family of curves, some feeling for the sensitivity of ε to disk and array tolerances should become feasible.

11. M. M. Z. El-Kharadly, Proc. IEE, 17-25 (1955). Dispersion characteristics of artificial dielectrics at centimeter wavelength are studied experimentally. A technique for measuring samples for their ε_r and Z within a parallel-plate waveguide simulator is carefully developed and calibrated. Dispersion curves for sphere arrays and disk arrays are given. It is of interest to observe in Fig. 7 that for 1/2" diameter disks with 1.5 cm spacing, over a range in λ from 8 cm to 11.5 cm, very little deviation from n = 1.27 occurred. Since the index is low for this case, interelement spacings are relatively high, thus mutual coupling low. For higher index where coupling effects become high, the dispersion may be higher. Nonetheless, the fact that virtually no dispersion is observed here is encouraging in concluding that the disk array can be operated very broadband.

The mechanisms for dispersion are cast also into two categories: (a) dipolar dispersion, or those associated with resonances of the particle itself, and (b) cavity resonance, or those related to interelement interactions. What is stated as a commonly accepted criterion is that for low dispersion operations, the wavelength should exceed ten times the largest element dimensions involved.

Results for strip arrays and rod arrays are also presented.

12. J. Brown and W. Jackson, Proc. IEE, 11-16 (1955). Some potential problems associated with using artificial dielectrics at centimeter wavelengths are introduced. It is pointed out that static theory predictions for μ and ε may not be applicable because of dispersion. A hypothesis is advanced that since at higher frequencies, μ and ε may not be easily separ-

able, a better performance measure would be the propagation constant β and wave impedance Z. (The formal proof for the validity of these concepts starting from Maxwell's equations through Poynting theorem is given in the appendix.)

An observation is made that phase change versus distance in artificial dielectrics does not follow a straight line, but rather takes on quantum jumps. The reactive fields at interfaces is also a problem. An interesting conclusion is again restated: Artificial dielectrics generally commence to show dispersion when the wavelength is less than ten times the largest cell dimension.

13. Z. A. Kaprielian, J. Appl. Phys., 24-32 (1956). A formal and elegant theoretical treatment for the circular disk lattice is presented. The ideas are as follows. The molecular theory used by Kock assumes that the total E-field acting on each element is the externally applied field. Neighboring elements, however, may also contribute to this field, and this is now included as dipole fields. An assumption is still made that mutual interactions do not alter the field structures so that one can use dipoles only, no multipoles. Thus the model would be accurate only when we have small elements separated "medium" far. (Close enough so neighboring dipole fields need to be included but not so close as to distort the fields enough that simple dipole field descriptions no longer suffice.)

Expressions for static fields from an isolated dipole are first defined. Next the sum of contributions from all elements in the lattice is written, as a triple sum. This is in turn written in matrix form for general arbitrary lattices. For a tetragonal lattice the matrix reduces to a diagonal tensor for the permittivity. Each term must then be carefully treated since the triple sums are only conditionally convergent. To unravel this, each series is first recast into a form convenient for Poisson transformation. For the triple series, the transforming is next taken. After some tricky manipulations, a startling conclusion results. For a cubic lattice, the formal treatment here reduces exactly to the Clausius-Mossotti form for permittivity

$$\varepsilon_r = k_{exx} = 1 + \frac{N\alpha/\varepsilon_o}{1-(\alpha N/3\varepsilon_o)}, \quad \alpha = \text{polarizability of disk.}$$

Thus it may be concluded that the Clausius-Mossotti approximation is a rather accurate one even for rectangular lattices, since it is equivalent to this formal theory for a cubic lattice.

For arbitrary lattice structures, a scheme is proposed whereby it is approximated outside a central region as a cubic lattice. In the center region the actual lattice structure would be needed.

The examples cover a cubic array of ferrite spheres and a tetragonal array of circular disks. For the disk, polarizabilities predicted by Rayleigh are used. The results for ε_r in Fig. 4 thus calculated agreed well with measurements provided the layer spacings are large. (Generally layer spacing/cell width ratios greater than 0.7.) The same comparison was later done by Cohn (1956) and more conclusive evidence can be found there.

14. J. Brown and J. S. Seeley, Proc. IEE, 465-471 (1958). The interface reactive fields of an artificial dielectric are examined. This detailed scrutiny is felt needed because the interface layer sees an essentially different environment than interior layers. The analysis uses transmission line modeling. Modal expansion and boundary matching methods are used. The numerical results obtained (reflection coefficient) used only the first evanescent mode of the expansion and agree with measurements.

For lens design, especially at relatively low refractive index, the interface reflection problem should be of only secondary importance.

15. Z. A. Kaprielian, J. Appl. Phys., 1052-1063 (1958). Anisotropic effects in isotropic lattices are examined theoretically. The analysis is an extension of earlier work of the author (1956). A dipole description of the interaction is used, but time harmonic Green's function is used to calculate fields. The polarizability for the elements is still from static theory. Thus, in spite of the fact that lattice spacings may now be large electrically, particle sizes still need to be small.

Four types of anisotropy mechanisms for a lattice of particles are found:

a) Structural anisotropy associated with the lattice. (e.g., cubic, rectangular, or random)

b) Element anisotropy arising from how particles polarize, or respond to applied field.

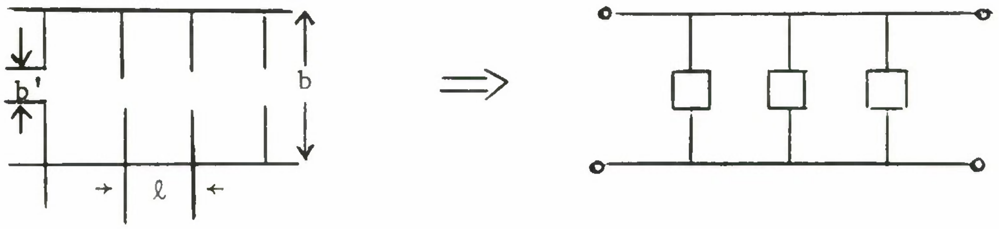
c) Physical shape of the elements.

d) Granularity of the lattice, causing anisotropy at high frequencies.

The theoretical development is again elegant but complex. The fields are written as triple sums, which are in turn reduced through Poisson transformation. It is shown in passing that if the sums were written as integrals, and trapezoidal rule used, then the results reduce to the Clausius-Mossotti relationship. Propagation constant expressions are derived and limited results shown, demonstrating anisotropy.

16. G. P. Srivastava, P. C. Mathur, and A. Kumar, J. Appl. Phys., 2674-2675 (1971). Using Lewin's expressions for ε and μ for an artificial dielectric of spherical particles, Faraday rotation (from μ) is computed for semiconductor materials. Contributions to rotation are found to be "significant."

17. S. B. Cohn, Journal of Applied Physics, Vol. 20, 257-262, 1011 (1949). Metal strip type artificial dielectrics suitable for linear polarization applications are analyzed via transmission line equivalent circuit methods. A review of the molecular theory of Kock is first given. It is pointed out that because it is static, the operating wavelengths must be large, and the strips far apart because mutual interactions are not properly accounted for. The transmission line approach is next introduced by inserting waveguide walls perpendicular to the electric field. Next the equivalent circuit thus established is analyzed using cascading network theory to give the overall n and Y_I (refraction index and normalized admittance).



The claim is made that for $\ell > b$, then the shunt susceptance for isolated capacitive iris (when b/λ is also small) may be used where

$$B = \left(\frac{4b}{\lambda}\right) \ell n \csc \frac{\pi b'}{2b}$$

Possible reactive field coupling when ℓ becomes small is not dealt with. (Note that the layer-to-layer interactions are included in the transmission line circuit but how these may in turn influence B itself is not known.) The result when T-line theory is applied is that the refractive index n

$$n = \frac{\lambda}{2\pi\ell} \cos^{-1} \left\{\cos \frac{2\pi\ell}{\lambda} - \left(\frac{B}{2}\right) \sin \frac{2\pi\ell}{\lambda} \right\}$$

It is interesting to note that the limit when $\lambda \to \infty$ for this theory does reduce to the molecular theory.

The idea of using quarter-wave transformers to reduce surface reflection is also pointed out, along with an emphasis of how easy it can be accomplished (by merely making the strip width of the first and last layer smaller).

The transmission line model also gives dispersion characteristics. When $\ell < b$, it was found necessary to introduce an additional bridging capacitance to include in the changes in B due to layer-to-layer coupling. These were done somewhat artfully, but not altogether believably, by extrapolating from stepped transmission line models. The important features established seem to be that these additional shunt capacitances are needed to more accurately account for coupling.

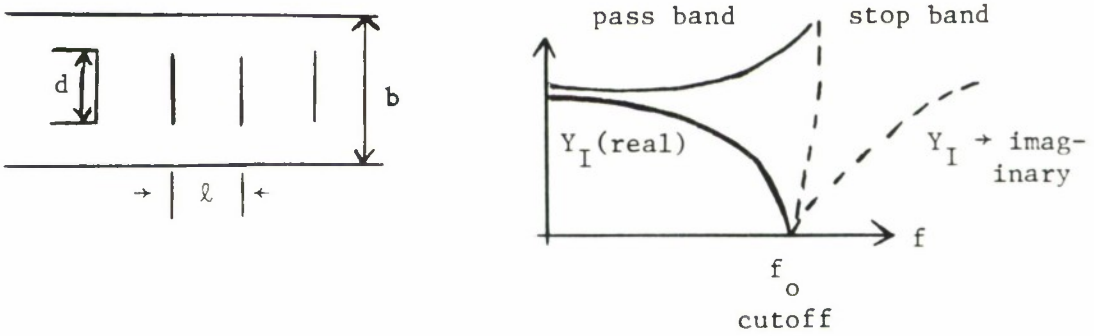
Measured patterns were claimed to have been made and looked similar to Kock's (even though they are not explicitly shown). Results presented in Fig. 14 demonstrate that with surface matching, the measured VSWR can be reduced from 2 to 1.2 over a band of from 4.4 GHz to 5.5 GHz.

18. S. B. Cohn, J. of Appl. Phys., Vol. 21, 674-680 (1950). The susceptance for variously configured disk type artificial dielectrics is measured using an electrolytic-tank analog. Refraction index is then determined using using T-line formulas. The geometries are: tetragonal array of rectangular plates, tetragonal and hexagonal array of circular disks.

The failure of the molecular theory to account for frequency dependence is first used to justify T-line modeling. For complex shapes, in particular, three-dimensional plates, susceptance needed for the T-line formulas is not available. Consequently, electrolytic tank measurements are needed to determine these. A careful examination first reveals that appropriate electric and magnetic walls may be inserted in the array without disturbing the fields. Using then the duality:

Fields	Electrolytic
electric walls	conducting walls
magnetic walls	insulating walls
D or E	I or i
Capacitance	conductance

the utility of the tank analog where resistances are measured with a bridge becomes apparent. Susceptances for variously configured arrays are presented in Figs. 7 (square), 8 (circle with square distribution), and 9 (circle with hexagon distribution). The conversion of these susceptances into refraction index via transmission line models faces a major drawback.



If the section lengths ℓ are large enough, then bridging capacitances, which tell how much layer-to-layer interaction may affect the B itself, may be ignored. From experience, this is said to be at $\ell/b > 0.75$. There exists no way of measuring these bridge capacitances in the electrolytic tank. Generally, the effect of the bridge capacitances is to make the roll-offs of n and Y away from low frequencies to occur more quickly and severely.

Ignoring these, then index of refraction may be calculated from formulas given in an earlier paper (1949).

Useful results for n are presented in Figs. 11-13 for various d/b versus ℓ/b. Experience also seems to indicate that these are applicable for $b/\lambda \leq 0.25$, and quite accurate for $b/\lambda < 0.1$.

19. S. B. Cohn, Jour. of Appl. Phys., Vol. 22, 628-634 (1951). Effect of thickness of disks on artificial dielectrics is studied using electrolytic tank measurement methods. A review of theory established before is first made. Babinet equivalence is also established between arrays of plates and apertures.

The influence of thickness of objects is that the magnetic fields will now be disturbed, with a resulting decrease in the permeability, and correspondingly lowering of the refraction index. Theoretical predictions of μ changes use perturbation techniques, for the case when thickness is small compared to diameter. Agreement between measurement and theory is demonstrated to be good (for $0 < t/b < 0.05$ in Fig. 6). Application to a specific example, Fig. 7, finds that for b = 1" (cell width), d/b = 0.68 (d = diameter of disk) and thickness t = 0.01", then the index n only changes by 1% from 1.4. Thus in practical construction techniques where disks are metal-sprayed on, the diamagnetic effect of thickness is indeed negligible.

20. S. B. Cohn, Proc. IRE, 1416-1421 (1951). Aperture parameters are obtained by electrolytic tank measurements. Babinet equivalent is not strictly used. Rather a new electrolytic tank configuration is carefully derived which corresponds to aperture cases. Measured polarizabilities are

presented for square apertures, rectangle with rounded ends, dumbbells, cross, and rosette shapes.

21. S. B. Cohn, Proc. IRE, 696-699 (June 1952). Electrolytic tank measurements for polarizability of "large" apertures are performed. The addition of an empirical frequency correction factor to Bethe's small hole theory now allows consideration of arbitrarily shaped apertures up to first resonance. Attenuation and susceptance curves for various shapes are supplied.

22. S. B. Cohn, Proc. IRE, 1069-1071 (September 1952). The electric polarizability of large apertures was measured using electrolytic tank techniques.

23. S. B. Cohn, J. of Appl. Phys., Vol. 24, 839-841 (July 1953). Experimental results for the metal strip dielectric were presented in an effort to determine the most accurate theoretical model. Four theories were used:

1. Molecular theory of Kock
2. Transmission line model of Cohn using susceptance of isolated iris
3. T-line with bridging shunt capacitances to correct for B of iris under layer-to-layer interaction (also of Cohn)
4. T-line with series inductances to correct B (of Sharpless)

Five experimental strip medium models were also considered, with varied width to spacing ratios. Three of these were measured in a waveguide simulator, while two were performed in free space using a dielectrometer. All were

tested as a function of frequency for cell spacings of 0 to 0.5λ. The primary conclusion is that theory three is the most reliable since it gave the lowest deviations from the measured refractive index.

Two independent observations not mentioned in the paper are as follows. Theory (1) appears to be better than (2). Thus layer-to-layer coupling, though only statically included in (1), but not so carefully done in (2), will play a fairly significant role. In addition, because measured refractive index n is displayed as a function of b/λ, conclusions of possible dispersionless operations can be drawn from the flatness of the curves. In general, little dispersion is indeed present for $b/\lambda < 0.25$, i.e., lattice spacings smaller than quarter wavelength.

24. S. B. Cohn, J. Appl. Phys., Vol. 27 1106-1107 (1956). Tetragonal array of circular disks is treated. Cohn's measurements for ε_r are shown to agree quite closely with those measured by Kharadly and Jackson. Two theories, by Kaprielian (pure static) and Brown and Jackson (static but views closely spaced stack of disks as cylinder) are also shown in contrast. Brown and Jackson's theory agrees closely with measurements, thus appears more reliable.

25. A. F. Wickersham, Jr., J. Appl. Phys., Vol. 29, 1537-1542 (1958). Single and double layers of arrays of rectangular strips are studied. Both the case of a rectangular lattice and a random lattice are measured. Both the refractive index and transmission loss are experimentally determined using an S-band dielectrometer for normal and oblique incidence cases. Five different sample configurations are used. The results in general indicate

that for higher n, closer spacings are needed with more dispersion; while at lower n, the structure becomes wideband (e.g. Fig. 4). These trends, together with the apparent incidence angle and polarization sensitivity, appear more useful in design of resonant surfaces rather than lenses.

26. E. M. T. Jones and S. B. Cohn, J. Appl. Phys., 452-457 (1955). The use of a layer of artificial dielectric to match out interface reflections of solid dielectric lenses is presented. Proper matching not only causes increase in power gain, but it also reduces sidelobes and backlobes as well as lowering the feed horn to lens VSWR.

Three schemes are possible: (1) an inductive wire grid buried $\lambda/8$ within the dielectric, (2) a capacitive circular disk array $3\lambda/8$ inside the dielectric, or (3) quarter wavelength layer of another solid dielectric whose $Z_m = \sqrt{Z_o Z_\ell}$ (where Z_ℓ is that of the lens itself). For the wire grid, MacFarlane's strip susceptance is used. Performance (theoretical) is good for $\theta < 30°$ from broadside, as given in Fig. 4.

For the disk array matching configuration, because all angles of incidence are of interest, Cohn's former T-line model is inadequate. Instead by a Babinet equivalent of the Bethe aperture theory, susceptance and then in turn reflection coefficient are obtained. Figures 5 and 6 show again good matching performance (theoretical) on a $n = 1.57$ lens.

Waveguide measurements for susceptance of one layer of circular disk (at 3 incidence angles) are made for different lattice configurations. Good agreement with Bethe theory is found for disk diameter $< 0.3\ \lambda$.

27. E. M. T. Jones, T. Morita, and S. B. Cohn, IRE Trans. AP, 31-33 (January 1956). Experimental verification for lens matching capability of artificial dielectrics is given. A polystyrene lens (n = 1.59) was matched with either a capacitive layer (array of disks) or a solid dielectric $\lambda/4$ transformer. The results are:

	unmatched	capacitive	$\lambda/4$ layer
sidelobes	-20 dB	-35 dB	-30 dB
gain	---	0.35 dB improvement	0.1 dB
VSWR	1.6	1.02	1.05
bandwidth	---	8.46 GHz to 12.2 GHz	

Details for the disk geometry are also supplied. They are:

	flat side of lens	curved side of lens
cell spacing	0.4"	0.221" to 0.277"
disk diameter	0.221"	0.283" to 0.325"
depth imbedded	0.283"	

Disks are formed by spraying silver paint.

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This report is based on a survey of the literature on phase-delay artificial dielectrics to examine their suitability for multiple-beam antennas for satellite communications. The conclusions are that arrays of conducting discs appear to be suitable for such application because they can be used with circularly polarized fields and can be built with a desirable index of refraction, in the neighborhood of 1.5. A review of theoretical and measured results is presented, with formulas and curves permitting selection of parameters and permitting determination of the effect of tolerances and of frequency variation. No information was found on the inherent loss of such a medium. In the appendix, digests of 27 selected papers on the subject are presented.

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